FAILURE PROCESS IN CONCRETE UNDER STATIC AND IMPACT TENSILE LOADING: EXPERIMENTS AND NUMERICAL MODELLING

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Abstract

A phenomenological rate-dependent model has been developed that successfully captures the structural behaviour of concrete at macroscopic level. However, failure of concrete is linked to processes at a lower scale, e.g. meso-scale. Without knowledge on the failure mechanisms at meso-scale, a proper prediction of failure under explosive loading conditions is not possible. Although the proposed macroscopic model gives an indication of the fracture process zone, fracture patterns are not realistically reproduced. Therefore, a mesoscopic model is developed that includes the meso-structure of concrete. In this paper, both macroscopic and mesoscopic models are presented and computational results have been compared with experimental results, with emphasis on global stress-displacement data as well as local fracture patterns.

1. INTRODUCTION

The response of concrete structures exposed to impulsive loading is an important safety issue. Safety assessment and design of protective buildings require an improved knowledge on the failure processes under impact and explosive loading. In the design process, the mechanical response of concrete structures is often predicted with numerical material models in a finite element context. Phenomenological rate dependent models are developed that can successfully capture the behaviour of concrete at macro-scale. However, failure is related to processes that take place at a lower scale, the meso-scale. Without knowledge on the failure mechanisms at meso-scale and the influence of the loading rate on crack patterns and damage development, a proper prediction of failure processes in concrete under impulsive loading conditions is not possible.

Therefore, failure processes of concrete under impulsive loading are experimentally studied by means of microscopic research. The capability of the developed macroscopic model is evaluated and numerical simulations are compared with experimental data, such as global stress-displacement curves and local failure data. A mesoscopic model is developed
that includes the meso-structure of concrete in order to be able to capture the failure behaviour of concrete at a lower scale. The results from mesoscopic analyses are compared with experimental data as well as with numerical results from the macroscopic model, to clarify the necessity of including the meso-geometry in the numerical model when studying the influence of the loading rate on the failure behaviour of concrete.

2. EXPERIMENTS

The rate-dependent behaviour of concrete in tension can be divided into two regimes: the moderate rate regime \([10^{-4}\text{ GPa/s} - 50\text{ GPa/s}]\) and the high rate regime \([> 50\text{ GPa/s}]\). The cause of the rate dependency of concrete in the moderate rate regime is mainly related to moisture in the pore system and in the high rate regime to inertia at micro- and meso-scale. This paper focuses on the moderate rate regime and the influence of moisture on softening, strength and failure mechanisms.

Experiments are performed at two different loading rates: static loading rate as a reference \((10^{-4}\text{ GPa/s})\) and moderate loading rate \((50\text{ GPa/s})\) with a Split Hopkinson Bar (SHB) set-up. The SHB set-up consists of two vertical cylindrical aluminium bars (diameter 74 mm), between which the concrete specimen is glued. The measured strains at the bars and specimen and the deformations are synchronized and combined to reconstruct the stress-deformation curve [1]. The static tests are performed with a deformation controlled tensile test set-up. The displacements are measured directly at the notched specimen and are combined with the total tensile force to derive the stress-displacement curve. The strength and fracture energy can be determined from the curves. The maximum stress corresponds to the strength and the integrated curve represents the fracture energy.

The notched specimens are cylindrical and have a diameter of 74 mm and a length of 100 mm. The influence of moisture content on the rate dependency of concrete is analysed by using three different saturation levels. At an age of 28 days, the specimens are exposed to different environments for three weeks: (1) immersed in water (‘wet’), (2) dried in an oven of 50°C (‘dry’), or (3) placed in a controlled environment at 20°C and 50% relative humidity (‘normal’). The final saturation levels of the specimens are given in Table 1 together with experimental results on strength and fracture energy for static and SHB loading conditions.

Table 1. Experimental data on saturation, tensile strength \((f_t)\) and fracture energy \((G_f)\).

<table>
<thead>
<tr>
<th>Saturation [%]</th>
<th>(f_{t,\text{stat}}) [MPa]</th>
<th>(f_{t,\text{SHB}}) [MPa]</th>
<th>(f_{t,\text{SHB}} / f_{t,\text{stat}}) [-]</th>
<th>(G_{f,\text{stat}}) [N/m]</th>
<th>(G_{f,\text{SHB}}) [N/m]</th>
<th>(G_{f,\text{SHB}} / G_{f,\text{stat}}) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>11</td>
<td>3.05</td>
<td>4.73</td>
<td>1.5</td>
<td>105.5</td>
<td>138.6</td>
</tr>
<tr>
<td>Normal</td>
<td>48</td>
<td>3.30</td>
<td>5.58</td>
<td>1.7</td>
<td>120.2</td>
<td>120.4</td>
</tr>
<tr>
<td>Wet</td>
<td>81</td>
<td>2.05</td>
<td>6.35</td>
<td>3.1</td>
<td>80.3</td>
<td>167.1</td>
</tr>
</tbody>
</table>

It is observed that the concrete exposed to wet conditions exhibits a much more pronounced rate effect when compared to the other conditions. The cause of the strength increase in the moderate regime is believed to be the moisture in the capillary pores [2]. The free water in these pores is assumed to exhibit the so-called Stefan-effect causing a strength enhancement in concrete with increasing loading rate. The stress-displacement curves for static loading rate and the stress-deformation curves for moderate loading rate are presented, discussed and compared with the numerical results in sections 4 and 5.
In an attempt to better characterize the fracture behaviour of concrete in our experiments, the fractured specimens are impregnated with fluorescent epoxy and the local fracture patterns are studied with a microscope. Thin slices of concrete are prepared to determine the amount of cracking and the crack lengths in more detail. The cracks are digitalized and the lengths and widths are determined. The results and trends are given in section 5.

3. NUMERICAL MODEL

3.1 Visco elastic visco plastic damage model

A material model that properly accounts for the rate dependency of concrete should include the mechanisms responsible for the rate effect associated with moisture. These mechanisms can be included by considering visco-elastic terms. To this end, we elaborate on the visco-elastic plastic model proposed by Sercombe et al. [3]. This model is extended to account for visco-plasticity and damage. The model covers two different rate-dependent mechanisms: visco-plasticity representing the strength increase associated to micro-cracking processes, and visco-elasticity accounting for the rate effect related to moisture (Stefan effect).

Figure 1: Rheological representation of the applied rate dependent continuum model.

The phenomenological rate dependent model presented in [4] relates the strengthening phenomena to two viscosity terms in a coupled visco-elastic visco-plastic damage (VEVPD) model. Figure 1 shows a rheological representation of the model. A strain decomposition is assumed of the type \( \varepsilon = \varepsilon^e + \varepsilon^{ve} + \varepsilon^{vp} \), where the strain tensor is split into an elasticity-based damage part \( \varepsilon^e \), a visco-elastic part \( \varepsilon^{ve} \) and a visco-plastic part \( \varepsilon^{vp} \). The parameters \( \eta^d_1 \) and \( E_1 \) in the visco-elastic part represent the viscosity and the stiffness. In the visco-plastic part, \( \eta^d_2 \) accounts for the viscosity and \( f_{vp}^{1,\varepsilon} \) is a rate-dependent tensile strength. The hardening force \( q \) is dependent on the plastic strain \( \kappa \) to represent the softening behaviour. Furthermore, \( q \) is a function of the visco-elastic strain \( \chi \) and strain rate \( \dot{\chi} \). The elastic stiffness \( E_2 \) in the damage part depends on the evolution of the damage parameter \( \omega \), which is coupled to a brittleness parameter \( \beta_2 \). A detailed treatment and algorithmic aspects of the model are presented in [4].

Table 2. Selected model parameters in the VEVPD model for different degrees of saturation.

<table>
<thead>
<tr>
<th></th>
<th>( E_1 ) [MPa]</th>
<th>( E_2 ) [MPa]</th>
<th>( \eta^d_1 ) [MPa·s]</th>
<th>( \tau_2 = \eta^d(\dot{\chi}) ) [s]</th>
<th>( \beta_2 ) [-]</th>
<th>( f_{stat} ) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>35000</td>
<td>5000</td>
<td>500</td>
<td>1.0</td>
<td>200</td>
<td>4.0</td>
</tr>
<tr>
<td>Normal</td>
<td>35000</td>
<td>50000</td>
<td>5000</td>
<td>1.0</td>
<td>550</td>
<td>3.0</td>
</tr>
<tr>
<td>Wet</td>
<td>33000</td>
<td>60000</td>
<td>470000</td>
<td>1.0</td>
<td>375</td>
<td>2.0</td>
</tr>
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</table>
3.2 Mesoscopic model

Failure processes in heterogeneous materials like concrete originate from lower scales and predominantly from the meso-scale. In order to properly capture the fracture process of concrete, more detailed information from the meso-scale must be included in the numerical model. To this end, a mesoscopic model is developed with the aim of describing the integrated response of large aggregates, matrix and the interfacial transition zone (ITZ). Both matrix and ITZ are described by means of the VEVPD model while aggregates are assumed to be linear elastic. The mesoscopic model provides a more realistic representation of the meso-structure of concrete, as shown in Figure 2b. The aggregate density is 30% and this realization can be compared to the true composition of the concrete meso-structure in Figure 2a. In a first attempt, the aggregates are spherical and surrounded by an ITZ with a thickness of 0.5 mm.

Figures 2a-c: Comparison of the experimental (a) and numerical (b) meso-structures and the distribution of the tensile strength of the ITZ elements (c).

The average stiffness and density in the mesoscopic model must be comparable to that of the macroscopic model, so that the response of the mesoscopic model corresponds to that of the macroscopic model and experimental results. We adopt a Mori-Tanaka scheme to compute the stiffness and densities of the constituents at meso-scale.

The failure initiation and damage evolution is mainly controlled by the properties of the ITZ material, which is the weakest constituent in our mesoscopic representation of concrete. Therefore, global and local responses are sensitive to these properties [5]. In order to obtain a more realistic failure pattern the tensile strength of the ITZ elements is randomly computed from a Weibull distribution as shown in Figure 2c.

4. GLOBAL COMPARISON

In this section, the results obtained with the numerical macroscopic model are compared to experimental data at global level. The stress-displacement and stress-deformation curves of the experiments are also determined numerically, according to the measurement set-up and with input parameters as stated in Table 2. The mesoscopic model, which is expected to give more realistic local results, should also match the experimental results at global level.

4.1 Comparison of peak value

The peak value of the stress-displacement curve (static tests) or stress-deformation curve (SHB tests) represents the strength of the concrete sample. In the experiments the strength increases with increasing loading rate for all three moisture conditions (Figs. 3a-c). The wet samples experience a more pronounced strength increase compared to the other conditions.
The numerical simulations for the VEVPD macroscopic model and the mesoscopic model show a similar trend (Figs. 4a-f). The parameters $E_1$ and $\eta_1^{s}$, which together represent the strength increase due to the moisture in the pores, depend on the saturation level. A higher viscosity, which represents a higher water content, leads to a higher increase in strength. Therefore, the strength increase is most significant for the wet condition.

For the comparison with numerical results, the experimental curves are represented by a green area (Figs. 4a-f), which includes the different curves per test. However, it is possible that curves are crossing and therefore the green area may give a slightly distorted view of the experimental results. As Figures 4a-f show, the numerical macroscopic model captures the peak values of the experiments well. The mesoscopic model is also capable of capturing the increase in strength for the dry and wet concrete (Figs. 4a, b, e and f). However, the results on strength for the normal condition are underestimated (Figs. 4c and d).

### 4.2 Comparison of peak width

The shape of the stress-displacement or stress-deformation curve gives an indication of the failure behaviour. The width and sharpness of the peak reflect on the brittleness of the concrete. A sharp peak reflects a more brittle behaviour and a more localized width of the fracture process zone. A wider, blunt peak with more pre-peak nonlinearity is an indication for the existence of micro-cracks and therefore more ductile behaviour. The experimental curves (Figs. 3a-c) show that for wet and dry concrete, the peak becomes wider and blunt when the loading rate increases. This implies that micro cracking increases at higher loading rates. The normal concrete, on the contrary, shows a sharper peak when loading rate increases. The observations from the experimental curves are supported by local fracture data (section 5.1).

The numerical simulations with the VEVPD macroscopic model show a similar trend. The pre-peak non-linearity and width of the peak increases when the loading rate increases. For the mesoscopic model, this trend is even more pronounced.

When the numerical output of the VEVPD macroscopic model is compared to experiments, it is observed that the sharp peak of normal concrete under moderate loading rates is not fully captured. All other cases are well represented by the macroscopic model. The curves of the mesoscopic model under moderate loading rates are much wider and show far more pre-peak non-linearity compared to the experiments (Figs. 4b, d and f). This is due to the introduction of the weaker ITZ around the aggregate particles, which initiates micro-cracks before the macro-crack is formed. However, the parameters determining the strength of
the ITZ are not properly calibrated yet, introducing more micro cracking in the numerical simulations than in the experiments.

4.3 Comparison of descending branch

The descending branch of the curves represents bridging of the cracks and the formation of the final macro-crack. A steeper slope indicates faster formation of the macro-crack and therefore more brittle behaviour. Interlocking of aggregates and friction of the surfaces of the macro-crack cause the remaining stress in the tail of the descending branch. The experimental curves (Figs. 3a-c) demonstrate that the slope of the descending branch becomes steeper when the loading rate increases. Under moderate loading rate, the normal concrete has a steeper descending branch than dry and wet concrete.

In the numerical models the parameter $\beta_2$ is coupled to the damage evolution parameter $\omega$ and represents the softening behaviour, i.e. the slope of the descending branch and therefore the brittleness of the material. When $\beta_2$ increases, the brittleness increases and the slope of the descending branch becomes steeper. The damage part of the model depends on the strain rate.
and can, by redefining parameter $\beta_2$ as a function of the strain rate, account for the more brittle behaviour of concrete under moderate loading rates. Figures 4a-f show that an increasing brittleness $\beta_2$ leads to a steeper descending branch. The same trend as in experiments can be observed for the numerical macroscopic and mesoscopic model, i.e. the steepness and brittleness increase with increasing loading rate.

A comparison between experiments and numerical simulations demonstrates that numerical results obtained with the VEVPD macroscopic model are very close to the experimental data. However, the post peak behaviour of the dry concrete for SHB tests shows a higher ductility compared to experiments. The tails of the curves are similar for the model and experiments. The mesoscopic model does not capture the slope of the descending branches in the static tests as correctly as the macroscopic model. The slopes of the numerical SHB tests are similar to the experiments and the mesoscopic model is also capable of representing the distinctive kink in the descending branch.

5. LOCAL COMPARISON

Global data, like stress-displacement curves, can be well represented by the developed macroscopic model. However, fracture planes and failure mechanisms take place at mesoscale. To study the capabilities of the macroscopic and mesoscopic model to reproduce realistic failure zones and fracture planes under static and dynamic loading, the local output of the models is compared to the experimental fracture patterns.

5.1 Experiments

The crack patterns of the fractured specimens are studied with a microscope. Thin ($\approx 60 \mu m$) concrete sections are fabricated from the area around the macro-crack, with a maximum sample width of 3 cm. Therefore, the width of the experimental pictures of the fracture patterns are limited (Figs. 6, 7, 8 and 9). The length of the digitalized cracks are measured and divided into three categories: (1) macro-cracks where the sample was physically separated, (2) micro-cracks that are connected to the macro-crack and (3) micro-cracks that are isolated from the macro-crack. The experimental results on fracture lengths and width of the fracture zone are shown in Figure 5 and Table 3.

From the experimental results on crack lengths it can be concluded that, compared to normal concrete, wet concrete has a larger total length of micro-cracks for SHB tests while dry concrete has a lower total length of micro-cracks for static tests.

![Figure 5: Crack lengths for dry, normal and wet Static and SHB tests.](image-url)
It is also shown that for dry and wet concrete the total crack length increases with increasing loading rate. For normal concrete the total crack length and the length of connected cracks decrease with increasing loading rate. This is in accordance with the results on global stress-displacement and stress-deformation curves (section 4.2). By comparing the experimental data on fracture lengths with data on width of fracture zones, it can be concluded that longer crack lengths do not automatically lead to wider fracture zones. In Table 3, the width of the fracture zone for the macro crack and the width for the macro crack, connected- and long isolated micro cracks are presented. Although normal concrete has a large total length of cracks, the width of the fracture zone is small. The width of the fracture zone is determined by the horizontal distance between the most left and most right point of the macro- or long micro-crack. An important observation is that the crack width increases most with increasing loading rate for wet concrete and does not increase for dry concrete.

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<tbody>
<tr>
<td>Macro</td>
<td>6.9</td>
<td>6.8</td>
<td>5.2</td>
<td>6.3</td>
<td>4.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Macro+long micro</td>
<td>8.7</td>
<td>8.8</td>
<td>6.1</td>
<td>8.1</td>
<td>6.0</td>
<td>8.7</td>
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5.2 Macroscopic model

The macroscopic model gives an indication of the width and shape of the fracture zone by using a damage parameter $\phi$ ($0 \leq \phi \leq 1$). Damage equal to 1 indicates complete failure. The local data on damage profiles of the macroscopic model are plotted in Figures 6a-c and 7a-c. The damage profiles of the static tests (Figs. 6a-c) show, compared to normal concrete, an increase in width for dry concrete and a decrease for wet concrete. This is in accordance with the experimental results, shown in Table 3. The trend in SHB damage profiles is different than the experiments. The numerical simulations show the widest fracture zone for normal concrete, while experiments demonstrate the opposite (Figs. 7a-c). Although the trend of the SHB tests itself might not be correctly simulated, the trends when comparing static to SHB tests are well captured. In experiments, the width of the fracture pattern for dry concrete is not increasing with increasing loading rate, which is in agreement with the simulations, looking at only the highest damage levels (Figs. 6a and 7a). The width of the fracture zone is strongly increasing for normal and wet concrete (Figs. 6b-c and 7b-c).

Figures 6a-c: Static damage profiles of macro-model compared with crack pattern experiments (black lines and dots): dry (a), normal (b) and wet (c).
5.3 Mesoscopic model

The macroscopic model predicts the width of the fracture zone. Unfortunately, it does not capture the true fracture mechanisms because of the lack of detail on mesoscopic level such as aggregates and ITZ. The fracture patterns of the mesoscopic model are presented and compared with experiments in Figures 8a-c and 9a-c. Similar to the macroscopic model, the trends of the static tests are captured well. The dry concrete has the widest fracture zone and the other two are alike, both in experiments as well as in the simulations. The tendency to form more than one macro-crack in the simulations for dry concrete can also be encountered in experiments. Micro cracking around the grains in wet concrete is observed in experiments as well as in the simulations (Figs. 8c and 9c). The damage patterns for SHB tests are not in every aspect in accordance with the experiments. For all conditions, the width of the fracture zone increase with increasing loading rate, as in the experiments. However, the large width for dry concrete is not in agreement with experiments. The SHB simulation of the dry concrete shows a large amount of small micro cracks, which is not found in the experiments.
6. CONCLUSIONS

A phenomenological rate-dependent model has been developed that successfully captures the structural behaviour of concrete at macroscopic level. However, failure of concrete is linked to processes at a lower scale, e.g. meso-scale. Knowledge about the failure mechanisms at meso-scale is important for safety assessment and design of structures. Therefore, failure is studied experimentally and numerically at macro- and meso-scale.

Experimental and numerical data is obtained on strength, fracture energy and load-deformation relations for static and dynamic conditions for three moisture levels. Trends that can be observed in both experiments as well as numerical models are increasing strength and post-peak brittleness for increasing loading rate, an increase in width of the fracture zone for normal and wet concrete and no increase for dry concrete.

Although the proposed macroscopic model gives an indication of the width of the fracture zone and trends can be observed that are in accordance with experimental results, fracture patterns are not realistically reproduced with these phenomenological models. A first attempt with a mesoscopic model, which includes aggregate particles and interfacial transition zone into the numerical model, shows that the fracture patterns are more realistic and multiple fractures can be observed. When the input parameters of the mesoscopic model are properly calibrated, it should be possible to find an improved accordance with experimental global data and possibly even better agreement with experimental fracture patterns.

Macroscopic models are useful to predict the width of fracture zones at macro-scale and study general trends in fracture mechanisms. However, mesoscopic models generate more detailed information about the failure of concrete at meso-scale and therefore are a valuable tool in studying and understanding the failure behaviour of concrete under impulsive loading conditions.

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